Towards Dynamically Running Quadruped Robots: Performance, Scaling, and Comparison

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1 Hardware platforms and project ideas

The field of robotic research applying legged machines and robots is growing quickly, but it is still facing a major discrepancy of performance, quality, and complexity, compared to their biological counterparts.
A lack of appropriate off-the-shelf hardware platforms, a lack of open-access to dynamically running legged robot platforms, and missing comparative studies between existing quadruped platforms (mis)leads researchers to re-invent and re-design own quadruped robots, from the scratch. As research of legged locomotion should be the goal, and not research about its tools (the robots *per se*), this can be a frustrating and time consuming process. Research in dynamic legged locomotion would benefit from free and easy access to blueprints, and studies where different robot design choices can be tested and compared rigorously against each other. A future, better-performing platform could be assembled from the best-performing components (actuators, sensors, driver code, controllers) and principles (type of actuation, type of control, sensing, leg design, trunk design, compliant design) of existing systems.

We shortly present two quadruped robot platforms. CheetahCub-robot was developed at BioRob [1], of an older version with lower speed and capabilities [2]. Oncilla-robot was developed at BioRob/EPFL in cooperation with ResLab/UGhent. Both robot platforms use a four-segment, pantograph-based leg design [3], and are roughly similar in dimensions. Of the two platforms, Oncilla-robot is the successor of CheetahCub-robot, with more sensor capabilities (Table 1), improved actuation, but also higher complexity and cost. CheetahCub-robot and Oncilla-robot were designed with multiple purposes; one of them includes research on the pantograph-like leg structure, and its implications for dynamic locomotion.

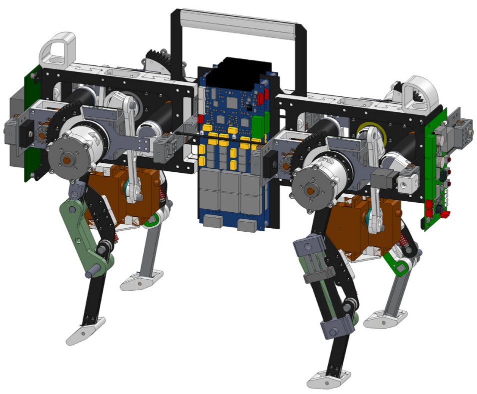
Oncilla-robot is being developed as the quadruped robot platform of the European AMARSi project, "... aim[ing] at a qualitative jump in robotic motor skills towards biological richness."[4], and is also meant to help comparing and analysing data from Biology and Robotics [5]. The entire Oncilla-robot platform will become open-source soon. This will include blueprints of all mechanical and electrical components and assemblies, firmware, communication, and driver programming code.

Due to its similarity in structure, both systems are easy to compare: CheetahCub-robot reached dynamic trot-gaits (up to $1.4\,\mathrm{ms^{-1}}$, 6.9 body lengths per second, Froude number[6] FR=1.3, cost of transport COT=$6\,\mathrm{JN^{-1}m^{-1}}$) [7]. CheetahCub shows self-stabilizing properties, where open-loop locomotion patters lead to decreasing pitch and roll angles at increasing robot speed. The robot also performed well at step-down obstacles, again without using sensory feedback. Oncilla-robot is currently undergoing rigorous tests, showing already good trot gait speed (v=$0.55\,\mathrm{ms^{-1}}$), at lower cost of transport, around COT=$3\,\mathrm{JN^{-1}m^{-1}}$. Hence, the effect of using stronger, more heavy motors and smaller gear box ratios is reflected by the lower cost of transport of Oncilla-robot.

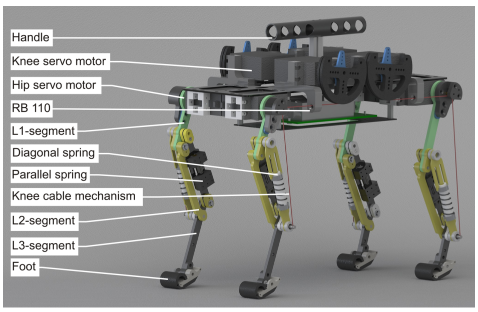
Oncilla-robot was designed with having certain drawbacks of CheetahCub-robot in mind. The RC servo motors of CheetahCub robot are modular, very compact and lightweight, easy to control, relatively cheap, and require not external control PCB. However, their small motor size (around $12\,\mathrm{W}$) and the extremely high gear ratio (around $300/1$) leads to a very high power consumption at fast and high frequency gaits, up to $10\,\mathrm{JN^{-1}m^{-1}}$. This showed to be a limit for long-lasting experiments, RC-servo motors defected at robot speeds higher than $1\,\mathrm{ms^{-1}}$, without taking long cool-down breaks. Oncilla-robot was designed with high-power ($90\,\mathrm{W}$) brushless motors, which can deal better with heat induced by fast oscillating motors, and rapidly switching, high torque profiles required for legged locomotion. Due to the high motor output torque, a lower gear ratio leads to better cost of transport performance. Equally, stronger motors allow for adequate load capabilities of Oncilla-robot. Hence, more sensors, and power on-board could be implemented. On-board sensing, improved actuation, and higher weight however also require a more expensive (10 times), more complex, and more load-bearing robot setup. From the existing results with CheetahCub we expect robot speeds up to $1\,\mathrm{ms^{-1}}$ with Oncilla robot, but with significant lower cost of transport, and typically at slightly higher gait frequencies, above $3\,\mathrm{s^{-1}}$.

Table 1: Rough comparison of CheetahCub-robot and Oncilla-robot. We use the Hildebrand version of the Froude number: $FR = v^2 g^{-1} L^{-1}$, with v the average robot speed, and the standing hip height as the leg length (L). Cost of transport is defined as COT$= Pm^{-1} g^{-1} v^{-1}$, with P the full electrical power consumption for locomotion, and m the mass of the robot.

	CheetahCub-robot	Oncilla-robot
Weight	1.1 kg	3.7 kg
Leg length, width foot-foot, hip-shoulder	0.15 m, 0.11 m, 0.21 m	0.17 m, 0.14 m, 0.225 m
Computation, communication, power on board	RB110, wireless and PWM 50 Hz, tether	RB110, wireless, RS485 high speed bus, battery on board
Sensors	RC-internal absolute encoder for hip and knee	IMU 9axis, 3x absolute joint encoders per leg, horizontal and vertical force sensing per leg, hip and knee relative encoders per leg, robot power consumption, RC servo encoder
Active DOF per leg	hip, knee	hip, knee, ablation
Leg design	pantograph, 3-spring system, 4 segments	pantograph, 3-spring system, 4 segments
Actuation per leg	2x RC servo motor	2x 90W brushless 4-pole motors, 1x RC servo motor
Gear ratio hip, knee, ablation	297/1, 297/1, none	84/1, 56/1, 297/1
Speed max trot, walk	1.4 ms^{-1}, 0.75 ms^{-1}	0.55 ms^{-1}, ...
FR max trot, walk	1.33, 0.38	0.33, ...
COT best, max FR	5.9 $JN^{-1}m^{-1}$, 10 $JN^{-1}m^{-1}$	3 $JN^{-1}m^{-1}$, ...



(a) Oncilla-robot, CAD



(b) CheetahCub-robot, CAD

Figure 1: Links to movies of both robots can be found in section 3. Both robots are roughly house cat-sized, CheetahCub being less heavy (1.1 kg) than Oncilla-robot (3.7 kg).

2 Open questions

Research questions for both robot platforms CheetahCub-robot and Oncilla-robot are related to the design of the mechanism, the controller, and the resulting gait characteristics. Above robot platforms are very similar in mechanics, this includes the leg design, but also the center of mass. With the upcoming development of bio-inspired quadruped and legged robots, it becomes interesting to identify required “blueprints”, and see their dependence on the expected gaits.

1. Leg design: Raibert’s quadruped robot design [8], featuring prismatic legs, and a three-parted controller proved that engineering a quadruped robot can work extremely well. Succeeding robots (BigDog [9], AlphaDog) seemingly feature similar base-controllers, but have switched to different leg design. The exact **influence of leg segmentation and leg design** will require more work, and presents a challenging task.

2. Until recently, **gait and locomotion controllers** for quadruped robots, at higher comparable speed, relied on feedback loops. Reflex-based controllers (e.g. CPG [10]) were implemented, or model based control (e.g. Scout 2 [11]). With CheetahCub-robot we can show that with the appropriate leg configuration, and an adapted controller, higher-speed, open-loop, and self-stabilizing locomotion is possible. We propose that for level-running, a robot should be capable of open-loop running, i.e. feedback, either model or reflex-based, should only be necessary when facing obstacles, or perturbations.

3. Somewhat like airplanes, legged robots such as quadruped robots require a low mass to size ratio, to succeed with high-speed gaits. Calculated, controlled passive deflections in leg or trunk structure can be advantageous. Compliant elements can reduce the robot

weight, by replacing actuators, and by redirecting, integrating, and accumulating/freeing forces and energies. However, simple, linear, and passive compliant systems typically restrict a robot system to one preferred frequency. How can one force or stimulate a simple **passive compliant system** into multi-mode locomotion with a large range of dynamics?

4. Together with intrinsic stability characteristics of the robot, the number and types of sensors define the robot's capabilities. Certain controllers require state estimations, e.g. a standard SLIP-like control would require the information of the instantaneous hip height, speed, and the leg angle in world frame coordinates. While off-the-shelve sensors become easier accessible nowadays, good quality ones can still be very expensive (IMU, load cells). **Which sensors, and which controller present a robust and easy to implement trade-off for a good legged robotic design?**

3 Material

Movie links to CheetahCub-robot and Oncilla-robot are available here:
`http://tinyurl.com/d3okppf` (CheetahCub-robot)
`http://tinyurl.com/crypjy8` (Oncilla-robot)

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